

The sensitivity of cosmic ray air shower experiments for leptoquark detection

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Abstract

Leptoquarks arise naturally in models attempting the unification of the quark and lepton sectors of the standard model of particle physics. Such particles could be produced in the interaction of high energy quasi-horizontal cosmic neutrinos with the atmosphere, via their direct coupling to a quark and a neutrino. The hadronic decay products of the leptoquark, and possibly its leptonic decay products would originate an extensive air shower, observable in large cosmic ray experiments. In this letter, the sensitivity of present and planned very high energy cosmic ray experiments to the production of leptoquarks of different types is estimated and discussed.

Key words: leptoquarks, UHECR, EAS, neutrinos, AGASA, Fly's Eye, Auger, EUSO, OWL

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1 Introduction

In this paper, the possibility of leptoquark searches in current (AGASA [1], Fly's Eye [2]) and future (Auger [3], EUSO [4], OWL [5]) very high energy cosmic ray experiments is discussed. The approach outlined in [6] is closely followed.

Leptoquarks arise naturally in several models attempting the unification of the quark and lepton sectors of the Standard Model (SM) of particle physics.

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Different leptoquark types are expected, according to their quantum numbers, which give rise to different coupling strengths and decay modes, and thus to different cross-sections and final states. The fact that leptoquarks provide a direct coupling between a quark and a lepton, charged or neutral, makes them unique particles, which should lead to signatures that have been thoroughly searched for at man-made accelerators. In fact, in the past years many searches were performed at colliders around the world [7]. Whereas in ep collisions at HERA leptoquarks could be s -channel produced, in all cases (ep , e^+e^- and hadron colliders) they could arise as t -channel mediators of SM-like processes. If light enough, leptoquarks could arise at accelerators as final state particles of specific processes. So far, no evidence for leptoquarks was found, and stringent limits were set at the electroweak scale. In fact, couplings and masses of leptoquarks are constrained indirectly by low energy experiment and by the precise measurement of the Z^0 width, and direct and indirect searches at accelerators have set constraints at higher energies. It should be noted that most limits obtained at accelerators are valid for first family leptoquarks only, as the initial beams involve first family charged leptons. This is not the case for some of the Tevatron results, and will be clearly stated in the discussion of the results.

Large cosmic ray experiments, covering huge detection areas, are able to explore the high energy tail of the cosmic ray spectrum, reaching centre-of-mass energies orders of magnitude above those of man made accelerators. Although having poorer detection capabilities and large uncertainties on the beam composition and fluxes, cosmic ray experiments present a unique opportunity to look for new physics at scales far beyond the TeV. Energetic cosmic particles interact with the atmosphere of Earth originating Extensive Air Showers (EAS) containing billions of particles.

Energetic cosmic neutrinos, although not yet observed and with very large uncertainties on the expected fluxes, are predicted on rather solid grounds [8]. Nearly horizontal neutrinos, seeing a large target volume and with negligible background from “ordinary” cosmic rays, are an ideal beam to explore possible rare processes [9]. In particular, if the available energies are high enough, the interaction of cosmic neutrinos with the atmospheric nuclei should create the ideal conditions for the production of leptoquarks, with dominance of s -channel resonant production. As the initial beam must contain all three neutrino flavours, one expects the production of leptoquarks of first, second and third family. The produced leptoquarks are expected to decay promptly into a quark and a charged or neutral lepton. The branching ratio into the charged and neutral decay mode depends on the leptoquark type.

2 Leptoquark production and decay

Leptoquarks are coloured spin 0 or spin 1 particles with non-zero baryon and lepton quantum numbers. They are predicted by different extensions of the SM. In this paper, we follow the conventions and theoretical framework formulated in [10], where the most general $SU(3) \times SU(2) \times U(1)$ invariant Lagrangian is given for each family as,

$$\begin{aligned} \mathcal{L} = & (g_{1L} \bar{q}_L^c i\tau_2 \ell_L + g_{1R} \bar{u}_R^c e_R) S_1 + \tilde{g}_{1R} \bar{q}_R^c e_E \tilde{S}_1 + g_{3L} \bar{q}_L^c i\tau_2 \boldsymbol{\tau} \ell_L \mathbf{S}_3 \\ & + (g_{2L} \bar{d}_R^c \gamma^\mu \ell_L + g_{2R} \bar{q}_L^c \gamma^\mu e_R) V_{2\mu} + \tilde{g}_{2L} \bar{u}_R^c \gamma^\mu \ell_L \tilde{V}_{2\mu} + \tilde{h}_{2L} \bar{d}_R \ell_L \tilde{R}_2 \\ & + (h_{2L} \bar{u}_R \ell_L + h_{2R} \bar{q}_L i\tau_2 e_R) R_2 + (h_{1L} \bar{q}_L \gamma^\mu \ell_L + h_{1R} \bar{d}_R \gamma^\mu e_R) U_{1\mu} \\ & + \tilde{h}_{1R} \bar{u}_R \gamma^\mu e_R \tilde{U}_{1\mu} + h_{3L} \bar{q}_L \boldsymbol{\tau} \gamma^\mu \ell_L \mathbf{U}_{3\mu} + \text{h.c.} . \end{aligned} \quad (1)$$

We can see that there are eighteen leptoquarks per family: nine scalars and nine vectors. We also notice that some of these are grouped into weak isospin doublets or triplets, which is referred to by its index (1 for scalar, 2 for doublet, 3 for triplet). As in [10] we assume that the couplings are diagonal in generation space.

It is assumed that only one of the chiral coupling constants is non-zero. In the case of ep collisions, it was shown [10], that qualitatively similar results could be obtained either by taking $\lambda_R = 0$ or $\lambda_L = 0$, where λ represents the coupling relevant to the leptoquark in question ($g_i, \tilde{g}_i, h_i, \tilde{h}_i$) as defined in Eq. (1). However for νp collisions, only the case $\lambda_L \neq 0$ is of interest otherwise the neutrino will not couple to the leptoquarks. So in the following we consider $\lambda_R = 0$. From the above Lagrangian we can easily derive the decay modes and coupling constants for neutrino induced leptoquark production. This is shown in table 1, where the listed leptoquarks can be of first, second or third family (family indices are omitted) and $D = d, s, b$ and $U = u, c$, as we neglect the top parton distribution function (PDF). Unless explicitly stated, in all our results we consider the leptoquarks for which the factor $\sqrt{2}$ in the couplings is not present. For these other leptoquarks the results can be obtained by a simple rescaling. In the table, the possible decay modes (charged and neutral or neutral only) of each leptoquark type are also indicated.

The processes shown in table 1 can thus occur for leptoquarks of the first, second or third family. For our range of energies we are probing very small values of x and the cross sections are comparable for the three families. In the following, first family leptoquarks will sometimes be taken as a case study, but all families will be considered in the result derivation.

All the processes in table 1 occur by s -channel. However, flipping the quark to antiquark in each case leads to an alternative reaction, this time mediated

Leptoquark	Interaction	Decay	Coupling
Scalars			
S_1	νD	$\nu D, \ell^- U$	$-g_{1L}, g_{1L}$
S_3^3	νD	$\nu D, \ell^- U$	$-g_{3L}, -g_{3L}$
S_3^-	νU	νU	$\sqrt{2}g_{3L}$
R_2^U	$\nu \bar{U}$	$\nu \bar{U}$	h_{2L}
\tilde{R}_2^U	$\nu \bar{D}$	$\nu \bar{D}$	\tilde{h}_{2L}
Vectors			
$V_{2\mu}^U$	νD	νD	g_{2L}
$\tilde{V}_{2\mu}^U$	νU	νU	\tilde{g}_{2L}
$U_{1\mu}$	$\nu \bar{U}$	$\nu \bar{U}, \ell^- D$	h_{1L}, h_{1L}
$U_{3\mu}^3$	$\nu \bar{U}$	$\nu \bar{U}, \ell^- \bar{D}$	$h_{3L}, -h_{3L}$
$U_{3\mu}^-$	$\nu \bar{D}$	$\nu \bar{D}$	$\sqrt{2}h_{3L}$

Table 1

Relevant processes for neutrino induced leptoquark production, assuming $\lambda_R = 0$. Here $D = d, s, b$, $U = u, c$, $\ell = e, \mu, \tau$ and $\nu = \nu_e, \nu_\mu, \nu_\tau$.

by u -channel leptoquark exchange, as it is shown in Fig. 1. All the relevant amplitudes are given explicitly in [10] for eq interactions and can be easily adapted to our νq case, so we will not repeat them here. The contribution from s -channel resonant production is largely dominant up to moderate values of λ . In fact for values $\lambda \leq 5$ the width is small compared with the leptoquark mass and the differential cross-section is strongly peaked on the x value corresponding to the resonance pole, $x = m_{LQ}^2/s$, which gives the main contribution to the total cross-section. For this range of λ the narrow-width approximation [10]

$$\sigma(\nu p \rightarrow LQ) = \frac{\pi}{4s} \lambda^2 q \left(\frac{m_{LQ}^2}{s} \right) \times C_J \quad C_J = 1, 2 \quad \text{for} \quad J = 0, 1 \quad (2)$$

explains why the cross-section rises like λ^2 , as it is shown in Fig. 2. However, for larger values of λ the narrow width approximation can no longer be used and the dependence of the cross-section with λ begins to flatten out, depending on the energy of the incident neutrino. For these larger values of λ the u -channel is no longer negligible and has to be taken in account. Also, the leptoquarks with one or two decay modes, indistinguishable in the narrow with approximation, start to separate for larger values of λ . In Fig. 3 we plot the total cross-section as a function of the energy for different values of λ . As we intend to obtain sensitivities for values of λ that can be above the conditions of applicability of the narrow with approximation, in this work we

always performed the complete calculations, without any approximation.

The dependence of the total cross-section on the leptoquark mass is shown in Fig. 4 for a scalar and a vector leptoquark. The curves corresponding to other scalars (or vectors) of the same family are identical to these two.

All the figures above correspond to first family leptoquarks. In Fig. 5 the comparison of the total cross-section for the leptoquark S_1 of different families is shown as a function of incident neutrino energy. As expected, the observed differences are attenuated when the energy increases, as mass effects become less relevant.

3 Limits and sensitivities

3.1 Acceptances

The expected number of observed leptoquark events is given by:

$$\mathcal{N} = N_A \int \frac{d\phi_\nu}{dE_\nu} \sigma_{\nu N} \mathcal{A} \Delta T dE_\nu, \quad (3)$$

where $d\phi_\nu/dE_\nu$ is the incident neutrino flux, $\sigma_{\nu N}$ is the appropriate production cross-section, depending on which leptoquark type is considered, \mathcal{A} is the acceptance of the experiment for the extensive air showers produced by these final states, ΔT is the observation time interval and N_A is Avogadro's number. It is assumed that the attenuation of neutrinos in the atmosphere can be neglected, which is a safe assumption for total neutrino-nucleon cross-sections in the range relevant for the present study. For larger values of the cross-section, the treatment discussed in [11] should be applied. In this work the Waxman-Bahcall (WB) [12] bound with no z evolution, $E_\nu^2 \frac{d\phi}{dE_\nu} = 10^{-8}$ [GeV/cm² s sr], is assumed. The acceptance $\mathcal{A}(E)$ includes both the geometrical aperture, the target density and the detection efficiency factors. The procedure outlined in [6] was followed to obtain estimations of the acceptances of the different experiments [13,14,15,16]. The observation times were assumed to be: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For AGASA and Fly's Eye, we followed reference [13].

As noted in [6], the relation between the shower energy and the primary neutrino energy is process dependent. In the present case, it depends on the leptoquark type, which determines its decay branching fractions.

For the leptoquark charged decay mode (see table 1), all the energy of the primary neutrino will contribute to the development of the extensive air shower.

For the neutral decay mode, on the other hand, only the hadronic decay products will contribute. In general, the actual shower energy will depend on the branching ratio and on the $d\sigma_{\nu N}/dy$ distribution. From the convolution of the two, an average shower energy was obtained. The acceptances compiled in [6] were then considered.

3.2 Sensitivities for 1st family leptoquarks

Using equation 3, the sensitivity of the different experiments to leptoquark production, as a function of the leptoquark mass, was studied. Requiring the observation of one event, the sensitivity on the coupling λ (see section 2) as a function of the mass was derived. The expected sensitivities of the different cosmic ray experiments for 1st family leptoquarks of different types are presented in this section. The assumed observation times are the ones detailed above (and quoted in the caption of the figure).

Fig. 6 shows the sensitivity on the coupling λ as a function of the leptoquark mass expected in Auger, for different types of scalar and vector leptoquarks. As expected, better sensitivities are obtained for vector leptoquarks, due to the larger cross-sections. Other differences are due to coupling and branching ratio effects.

Fig. 7 shows the expected sensitivities of the different cosmic ray experiments, as a function of the leptoquark mass, for first family scalar and vector leptoquarks. Limits obtained at accelerators are also shown. It can be seen that for first family leptoquarks the powerful limits obtained at LEP (L3 indirect search) and HERA (which include both direct and indirect searches at H1) exclude the region that could be probed at large cosmic ray experiments, for the foreseen acceptances, observation time intervals and fluxes. As shown, low mass regions are also excluded by TEVATRON limits. Within the same family, the sensitivities for the different leptoquark types are within a factor of two. The indirect limits of H1 and L3 were linearly extrapolated to higher masses. In the TeV region, however, leptoquark width effects were taken into account, making these limits weaker.

3.3 Sensitivities for 2nd and 3rd family leptoquarks

As discussed above, cosmic ray experiments would allow to search for leptoquarks of all families, as the initial beam could contain all neutrino flavours. We can thus proceed to estimate the expected sensitivities for second and third family leptoquarks. These are shown in Fig. 8, for scalar leptoquarks, in the different considered experiments. In this case, most of the accelerator limits

discussed above no longer apply, and cosmic ray experiments could play a role. The D0 limits shown in the figure correspondent to scalar leptoquarks with both charged and neutral decay mode [7]. For third generation leptoquarks, the presently available limits are typically below 100 GeV/c².

Furthermore, for third family leptoquarks, an energetic tau lepton could be produced in the charged decay of a leptoquark. In these case, the double bang signature proposed in [17,18] could be searched for: the tau could travel long enough for its decay to produce a second shower, separate from the first one, but still within the field of view of the experiment. This rather distinctive new physics signature obviously requires a very large field of view, while the energy threshold for the observation of the second bang is also a critical issue. In fact, even for the experiments with the largest acceptances, only a few percent of the detected events are expected to have a visible second bang. Using the procedure detailed in [18], the sensitivity on the leptoquark coupling as a function of the mass from the observation of double bang events in EUSO was estimated. This curve is also shown in Fig. 8(b), where we see that we loose about one order of magnitude with respect to the sensitivity of the experiment.

4 Conclusions

The sensitivity of very large cosmic ray experiments for the production of scalar and vector leptoquarks of first, second and third family has been explored. While for first family leptoquarks most of the coupling and mass ranges that could be probed in cosmic ray experiments have already been excluded by indirect accelerator searches, relevant results could be obtained for second and third family leptoquarks. Also, double bang events could provide a distinctive signature, but only for very large acceptances or if the fluxes are larger than the ones considered.

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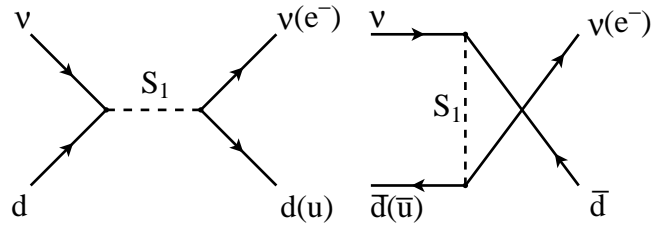


Fig. 1. Lowest order Feynman diagrams for leptoquark production in neutrino-quark collisions via s-channel (left) and u-channel (right) interactions.

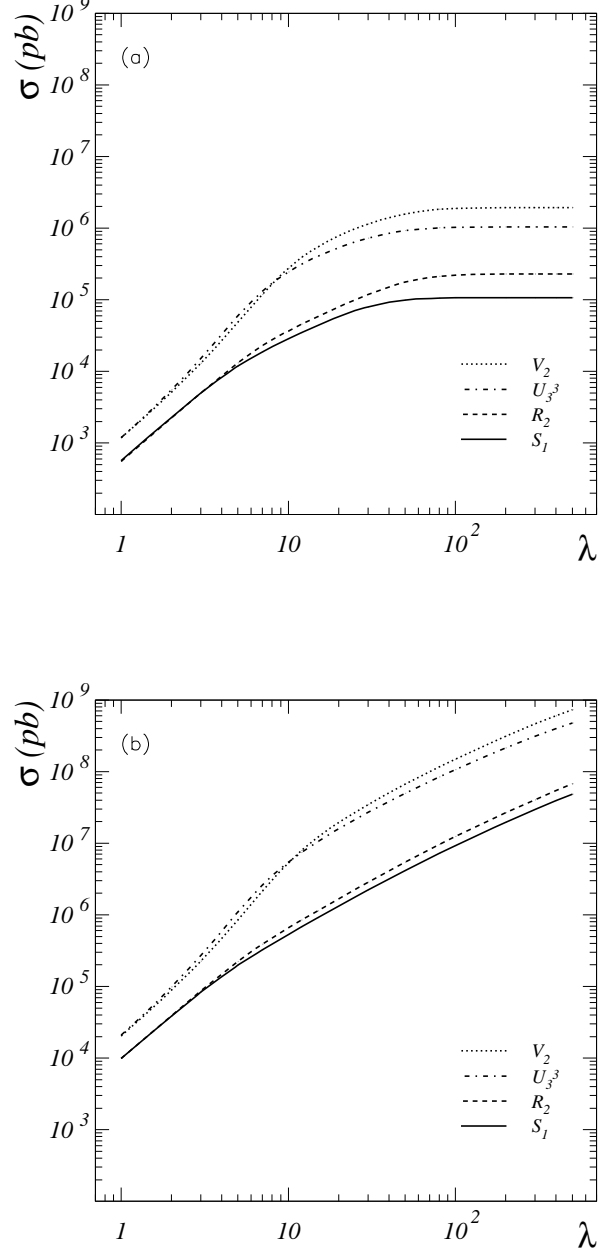


Fig. 2. Total cross-sections for scalar and vector leptiquarks, as a function of the coupling λ , for $M_{LQ} = 1$ TeV, and two different neutrino energies: (a) $E_\nu = 10^{17}$ eV, (b) $E_\nu = 10^{20}$ eV. The upper (lower) lines correspond to the cases of leptiquarks having two (one) decay modes.

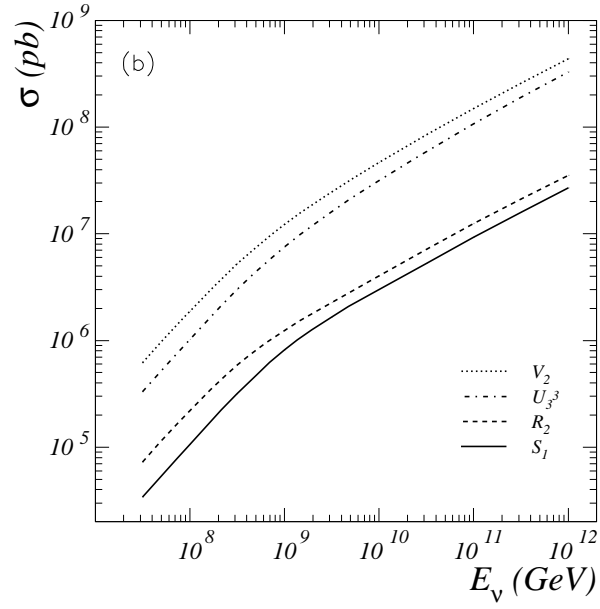
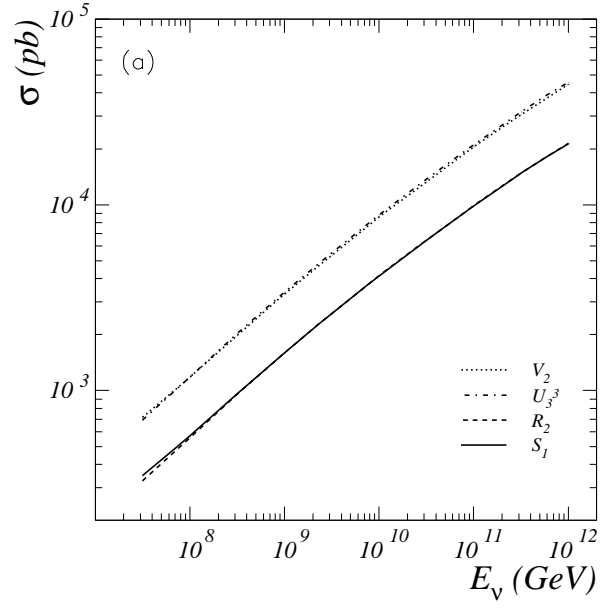


Fig. 3. Total cross-sections for scalar and vector first family leptoquarks, as a function of energy for $M_{LQ} = 1$ TeV, and two different values of λ : (a) $\lambda = 1$ and (b) $\lambda = 100$.

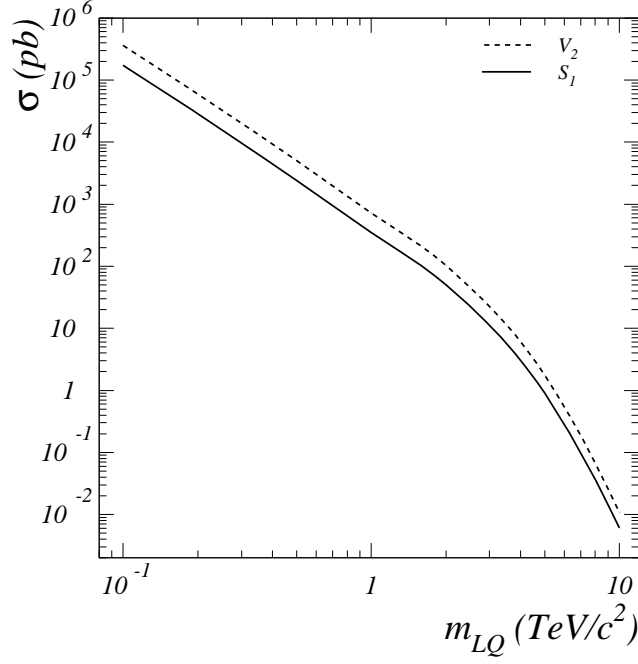


Fig. 4. Total cross-sections for scalar and vector first family leptoquarks, as a function of the leptoquark mass for $E = 10^{20}$ eV and $\lambda = 1$.

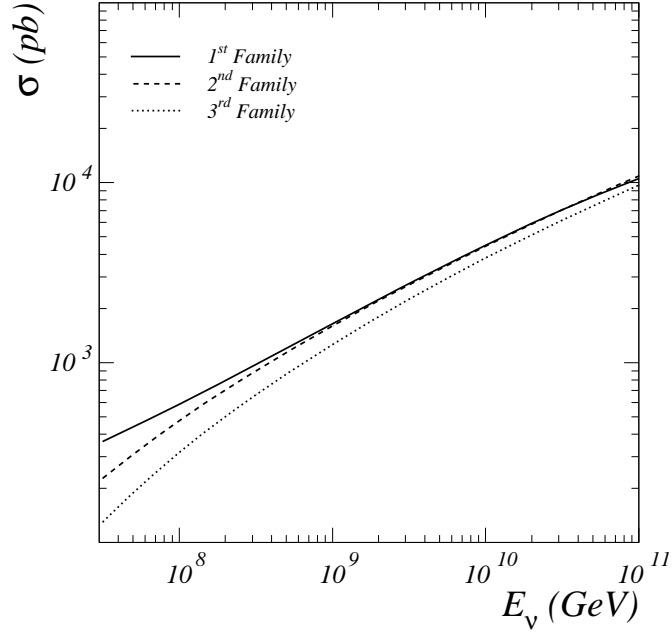


Fig. 5. Total cross sections for S_1 leptoquarks of different families, as a function of the incident neutrino energy, for $M_{LQ} = 1$ TeV and $\lambda = 1$.

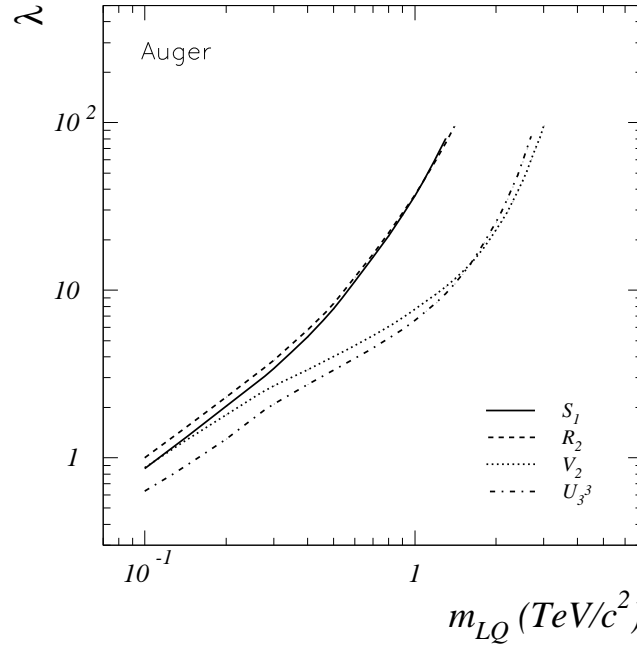


Fig. 6. Estimated sensitivities of Auger for different 1st family leptoquarks, as a function of the leptoquark mass, for an observation period of 10 years.

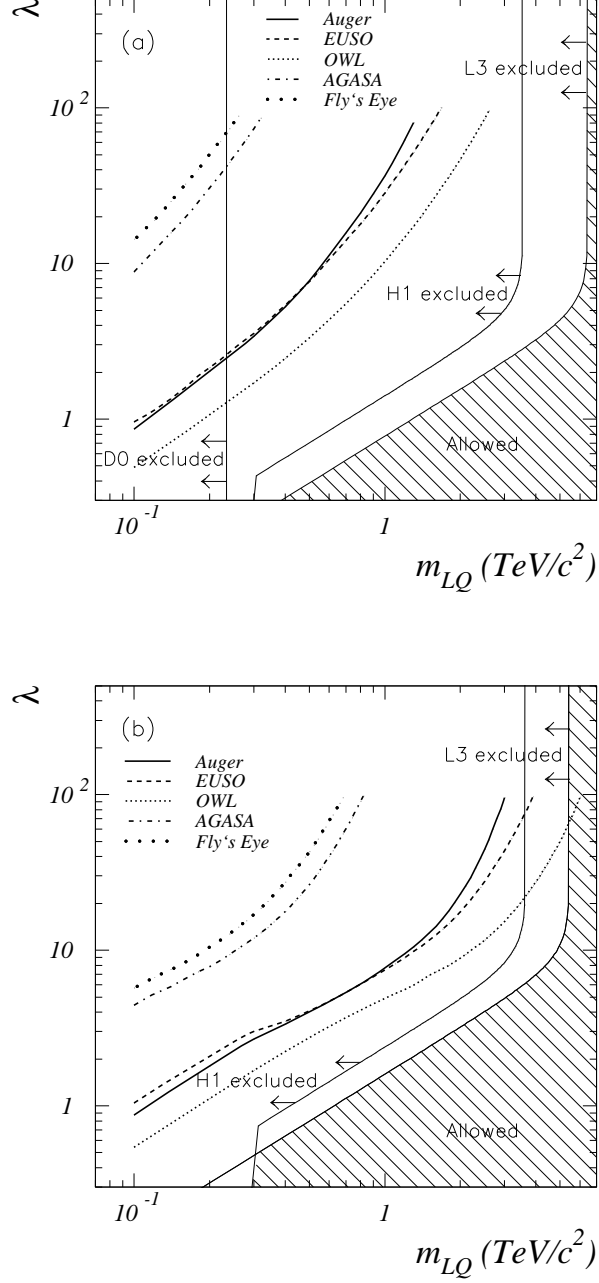


Fig. 7. Estimated sensitivities of the different cosmic ray experiments for scalar S_1 (a) and vector V_2 (b) 1st family leptoquarks, as a function of the leptoquark mass. The regions excluded by accelerator experiments are also shown (shaded regions) for comparison. The observation times were taken as: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For AGASA and Fly's Eye, we followed reference [13].

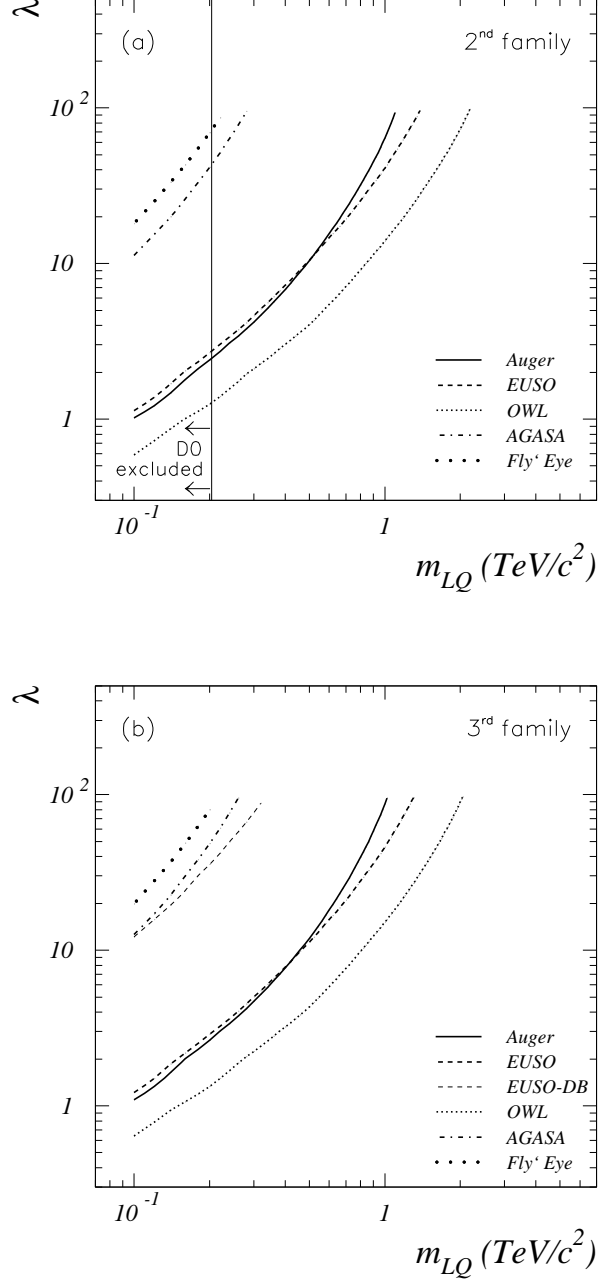


Fig. 8. Estimated sensitivities of the different cosmic ray experiments for S_1 leptoquarks of second (a) and third (b) family leptoquarks, as a function of the leptoquark mass. The observation times were taken as: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For AGASA and Fly's Eye, we followed reference [13]. In (b), the EUSO-DB line shows the expected sensitivity for double bang events (see text for details).